Energy and po er generation – Sankey diagram

ENERGY CONVERSIONS

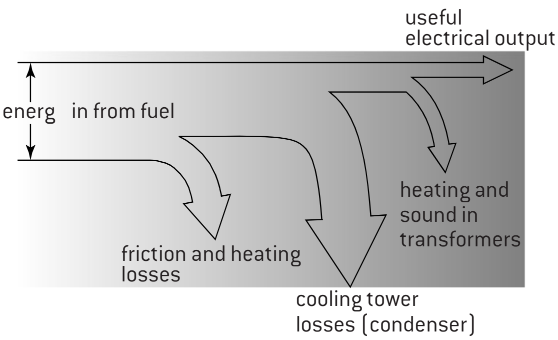
The production o electrical power around the world is achieved using a variety o di erent systems, o ten starting with the release o thermal energy rom a uel. In principle, thermal energy can be completely converted to work in a single process, but the continuous conversion o this energy into work implies the use o machines that are continuously repeating their actions in a fixed cycle. Any cyclical process must involve the trans er o some energy rom the system to the surroundings that is no longer available to per orm use ul work. This unavailable energy is known as **degraded energy**, in accordance with the principle o the second law o thermodynamics (see page 162).

Energy conversions are represented using **Sankey diagrams**. An arrow (drawn rom le t to right) represents the energy changes taking place. The width o the arrow represents the power or energy involved at a given stage. Created or degraded energy is shown with an arrow up or down.

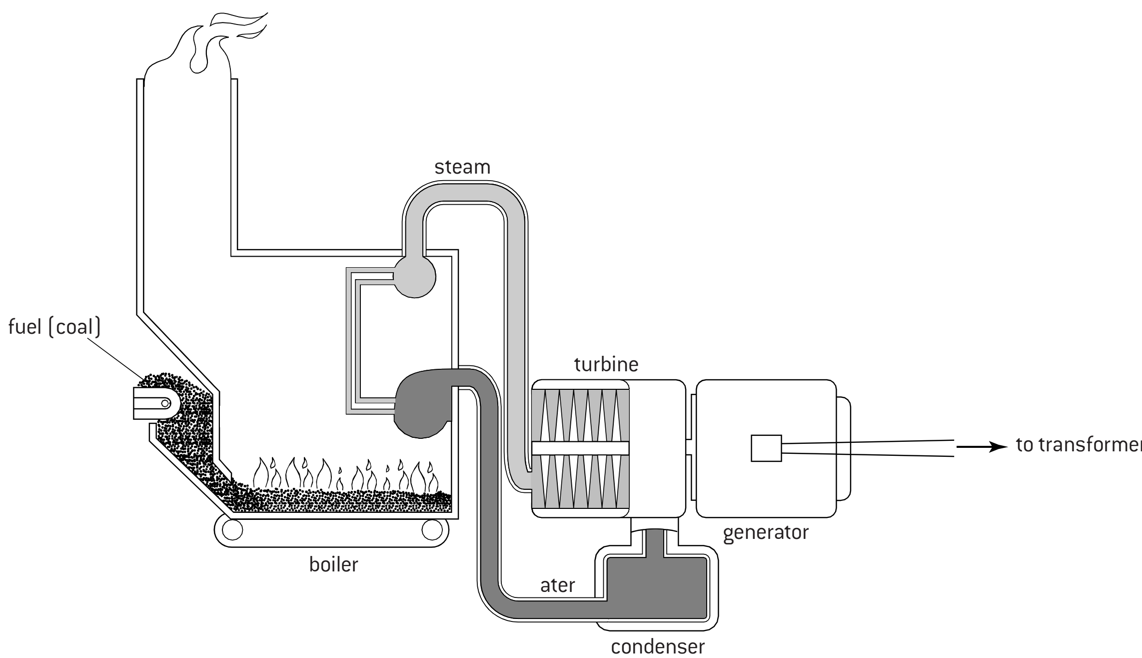
Note that Sankey diagrams are to scale. The width o the use ul electrical output in the diagram on the right is 2.0 mm compared with 12.0 mm or the width o the total energy rom the uel. This represents an overall e ficiency o 16.7%.

ELECTRICAL POWER PRODUCTION

In all electrical power stations the process is essentially the same. A uel is used to release thermal energy. This thermal energy is used to boil water to make steam. The steam is used to turn turbines and the motion o the turbines is used to generate electrical energy. Trans ormers alter the potential di erence (see page 114).



Sankey diagram representing the energy flow in a typical power station



Electrical energy generation

POWER

Power is defined as the rate at which energy is converted. The units o power are $J\ S^{-1}$ or W.

$$\text{Power} = \frac{\text{energy}}{\text{time}}$$

Primary energy sources

RENEWABLE / NON-RENEWABLE ENERGY SOURCES

The law o conservation o energy states that energy is neither created nor destroyed, it just changes orm. As ar as human societies are concerned, i we wish to use devices that require the input o energy, we need to identi y sources o energy. **Renewable** sources o energy are those that cannot be used up, whereas **non-renewable** sources o energy can be used up and eventually run out.

Renewable sources	Non-renewable sources
hydroelectric	coal
photovoltaic cells	oil
active solar heaters	natural gas
wind	nuclear
bio uels	

Sometimes the sources are hard to classi y so care needs to be taken when deciding whether a source is renewable or not. One point that sometimes worries students is that the Sun will eventually run out as a source o energy or the Earth, so no source is per ectly renewable! This is true, but all o these sources are considered rom the point o view o li e on Earth. When the Sun runs out, then so will li e on Earth. Other things to keep in mind include:

- Nuclear sources (both fission and usion) consume a material as their source so they must be non-renewable. On the other hand, the supply available can make the source **e ectively** renewable (usion).
- It is possible or a uel to be managed in a renewable or a non-renewable way. For example, i trees are cut down as a source o wood to burn then this is clearly non-renewable. It is, however, possible to replant trees at the same rate as they are cut down. I this is properly managed, it could be a renewable source o energy.

O course these possible sources must have got their energy rom somewhere in the first place. Most o the energy used by humans can be traced back to energy radiated rom the Sun, but not quite all o it. Possible sources are:

- the Sun's radiated energy
- gravitational energy o the Sun and the Moon
- nuclear energy stored within atoms
- the Earth's internal heat energy.

Although you might think that there are other sources o energy, the above list is complete. Many everyday sources o energy (such as coal or oil) can be shown to have derived their energy rom the Sun's radiated energy. On the industrial scale, electrical energy needs to be generated rom another source. When you plug anything electrical into the mains electricity you have to pay the electricity-generating company or the energy you use. In order to provide you with this energy, the company must be using one (or more) o the original list o sources.

SPECIFIC ENERGY AND ENERGY DENSITY

Two quantities are use ul to consider when making comparisons between di erent energy sources – the **specific energy** and the **energy density**.

Specific energy provides a use ul comparison between uels and is defined as the energy liberated per unit mass o   uel consumed. Specific energy is measured in J kg^{-1}

$$\text{specific energy} = \frac{\text{energy released rom uel}}{\text{mass o   uel consumed}}$$

Fuel choice can be particularly influenced by specific energy when the uel needs to be transported: the greater the mass o   uel that needs to be transported, the greater the cost.

Energy density is defined as the energy liberated per unit volume o   uel consumed. The unit is J m^{-3}

$$\text{energy density} = \frac{\text{energy release rom uel}}{\text{volume o   uel consumed}}$$

COMPARISON OF ENERGY SOURCES

Fuel	Renewable?	CO_2 emission	Specific energy(MJ kg^{-1}) (values vary depending on type)	Energy density (MJ m^{-3})
Coal	No	Yes	22–33	23,000
Oil	No	Yes	42	36,500
Gas	No	Yes	54	37
Nuclear (uranium)	No	No	8.3×10^7	1.5×10^{12}
Waste	No	Yes	10	variable
Solar	Yes	No	n/a	n/a
Wind	Yes	No	n/a	n/a
Hydro – water stored in dams	Yes	No	n/a	n/a
Tidal	Yes	No	n/a	n/a
Pumped storage	n/a	No	n/a	n/a
Wave	Yes	No	n/a	n/a
Geothermal	Yes	No	n/a	n/a
Bio uels e.g. ethanol	Some types	Yes	30	21,000

Fossil fuel po er production

ORIGIN OF FOSSIL FUEL

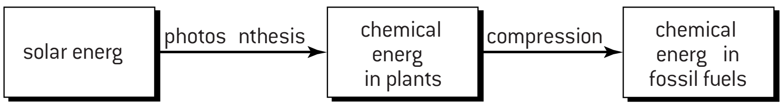
Coal, oil and natural gas are known as **fossil fuels**. These fuels have been produced over a timescale that involves tens or hundreds of millions of years from accumulations of dead matter. This matter has been converted into fossil fuels by exposure to the very high temperatures and pressure that exist beneath the Earth's surface.

Coal is formed from the dead plant matter that used to grow in swamps. Layer upon layer of decaying matter decomposed. As it was buried by more plant matter and other substances, the material became more compressed. Over the geological timescale this turned into coal.

Oil is formed in a similar manner from the remains of microscopic marine life. The compression took place under the sea. Natural gas, as well as occurring in underground pockets, can be obtained as a by-product during the production of oil. It is also possible to manufacture gas from coal.

ENERGY TRANSFORMATIONS

Fossil fuel power stations release energy in fuel by burning it. The thermal energy is then used to convert water into steam that once again can be used to turn turbines. Since all fossil fuels were originally living matter, the original source of this energy was the Sun. For example, millions of years ago energy radiated from the Sun was converted (by photosynthesis) into living plant matter. Some of this matter has eventually been converted into coal.



Energy storage in fossil fuels

EXAMPLE

Use the data on this page and the previous page to calculate the typical rate (in tonnes per hour) at which coal must be supplied to a 500 MW coal fired power station.

Ans er

Electrical power supply $= 500 \text{ MW} = 5 \times 10^8 \text{ J s}^{-1}$

Power released from fuel $= 5 \times 10^8 / \text{efficiency}$
$= 5 \times 10^8 / 0.35$
$= 1.43 \times 10^9 \text{ J s}^{-1}$

Rate of consumption of coal $= 1.43 \times 10^9 / 3.3 \times 10^7 \text{ kg s}^{-1}$
$= 43.3 \text{ kg s}^{-1}$
$= 43.3 \times 60 \times 60 \text{ kg hr}^{-1}$
$= 1.56 \times 10^5 \text{ kg hr}^{-1}$
$\approx 160 \text{ tonnes hr}^{-1}$

EFFICIENCY OF FOSSIL FUEL POWER STATIONS

The efficiency of different power stations depends on the design. At the time of publishing, the following figures apply.

Fossil fuel	Typical efficiency	Current maximum efficiency
Coal	35%	42%
Natural gas	45%	52%
Oil	38%	45%

Note that thermodynamic considerations limit the maximum achievable efficiency (see page 163).

ADVANTAGES AND DISADVANTAGES

Advantages

- Very high 'specific energy' and 'energy density' – a great deal of energy is released from a small mass of fossil fuel.
- Fossil fuels are relatively easy to transport.
- Still cheap when compared to other sources of energy.
- Power stations can be built anywhere with good transport links and water availability.
- Can be used directly in the home to provide heating.

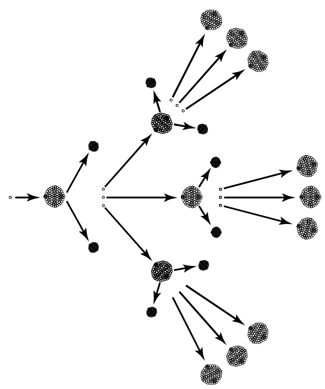
Disadvantages

- Combustion products can produce pollution, notably acid rain.
- Combustion products contain 'greenhouse' gases.
- Extraction of fossil fuels can damage the environment.
- Non-renewable.
- Coal-fired power stations need large amounts of fuel.

Nuclear power – process

PRINCIPLES OF ENERGY PRODUCTION

Many nuclear power stations use uranium-235 as the ‘fuel’. This fuel is not burned – the release of energy is achieved using a fission reaction. An overview of this process is described on page 76. In each individual reaction, an incoming neutron causes a uranium nucleus to split apart. The fragments are moving fast. In other words the temperature is very high. Among the fragments are more neutrons. If these neutrons go on to initiate further reactions then a chain reaction is created.



The design of a nuclear reactor needs to ensure that, on average, only one neutron from each reaction goes on to initiate a further reaction. If more reactions took place then the number of reactions would increase all the time and the chain reaction would run out of control. If fewer reactions took place, then the number of reactions would be decreasing and the fission process would soon stop.

The chance that a given neutron goes on to cause a fission reaction depends on several factors. Two important ones are:

- the number of potential nuclei ‘in the way’
- the speed (or the energy) of the neutrons.

As a general trend, as the size of a block of fuel increases so do the chances of a neutron causing a further reaction (before it is lost from the surface of the block). As the fuel is assembled together a stage is reached when a chain reaction can occur. This happens when a so-called critical mass of fuel has been assembled. The exact value of the critical mass depends on the exact nature of the fuel being used and the shape of the assembly.

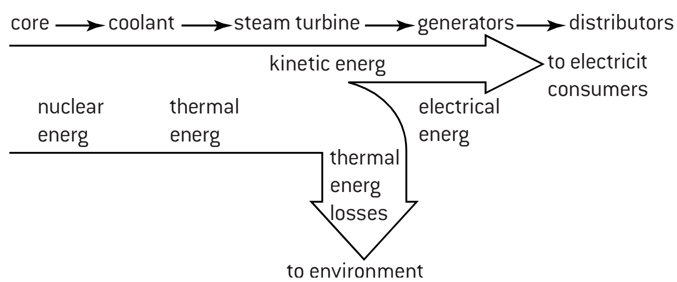
There are particular neutron energies that make them more likely to cause nuclear fission. In general, the neutrons created by the fission process are moving too fast to make reactions likely. Before they can cause further reactions the neutrons have to be slowed down.

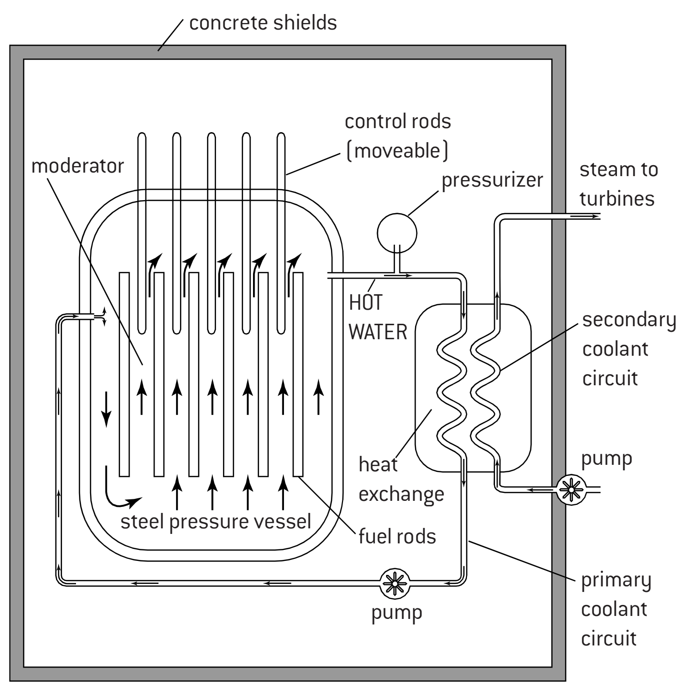
MODERATOR, CONTROL RODS AND HEAT EXCHANGER

Three important components in the design of all nuclear reactors are the **moderator**, the **control rods** and the **heat exchanger**.

- Collisions between the neutrons and the nuclei of the moderator slow them down and allow further reactions to take place.
- The control rods are movable rods that readily absorb neutrons. They can be introduced or removed from the reaction chamber in order to control the chain reaction.
- The heat exchanger allows the nuclear reactions to occur in a place that is sealed off from the rest of the environment. The reactions increase the temperature in the core. This thermal energy is transferred to heat water and the steam that is produced turns the turbines.

A general design for one type of nuclear reactor (PWR or pressurized water reactor) is shown here. It uses water as the moderator and as a coolant.





Pressurized water nuclear reactor (PWR)

ADVANTAGES AND DISADVANTAGES

Ad antages

- Extremely high ‘specific energy’ – a great deal of energy is released from a very small mass of uranium.
- Reserves of uranium large compared to oil.

Disad antages

- Process produces radioactive nuclear waste that is currently just stored.
- Larger possible risk if anything should go wrong.
- Non-renewable (but should last a long time).

Nuclear po er – safety and risks

ENRICHMENT AND REPROCESSING

Naturally occurring uranium contains less than 1% o uranium-235. Enrichment is the process by which this percentage composition is increased to make nuclear fission more likely.

In addition to uranium-235, plutonium-239 is also capable o sustaining fission reactions. This nuclide is ormed as a by-product o a conventional nuclear reactor. A uranium-238 nucleus can capture ast-moving neutrons to orm uranium-239. This undergoes β-decay to neptunium-239 which undergoes urther β-decay to plutonium-239:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U$$

$$^{239}_{92}U \rightarrow ^{239}_{93}Np + ^{0}_{-1}\beta + \overline{\upsilon}$$

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta + \overline{\upsilon}$$

Reprocessing involves treating used uel waste rom nuclear reactors to recover uranium and plutonium and to deal with other waste products. A ast breeder reactor is one design that utilizes plutonium-239.

HEALTH, SAFETY AND RISK

Issues associated with the use o nuclear power stations or generation o electrical energy include:

- I the control rods were all removed, the reaction would rapidly increase its rate o production. Completely uncontrolled nuclear fission would cause an explosion and **thermal meltdo n** o the core. The radioactive material in the reactor could be distributed around the surrounding area causing many atalities. Some argue that the terrible scale o such a disaster means that the use o nuclear energy is a risk not worth taking. Nuclear power stations could be targets or terrorist attacks.
- The reaction produces radioactive nuclear waste. While much o this waste is o a low level risk and will radioactively decay within decades, a significant amount o material is produced which will remain dangerously radioactive or millions o years. The current solution is to bury this waste in geologically secure sites.
- The uranium uel is mined rom underground and any mining operation involves significant risk. The ore is also radioactive so extra precautions are necessary to protect the workers involved in uranium mines.
- The transportation o the uranium rom the mine to a power station and o the waste rom the nuclear power station to the reprocessing plant needs to be secure and sa e.
- By-products o the civilian use o nuclear power can be used to produce nuclear weapons.

NUCLEAR WEAPONS

A nuclear power station involves controlled nuclear fission whereas an uncontrolled nuclear fission produces the huge amount o energy released in nuclear weapons. Weapons have been designed using both uranium and plutonium as the uel. Issues associated with nuclear weapons include:

- Moral issues associated with any weapon o aggression that is associated with war are. Nuclear weapons have such destructive capability that since the Second World War the threat o their deployment has been used as a deterrent to prevent non-nuclear aggressive acts against the possessors o nuclear capability.
- The unimaginable consequences o a nuclear war have orced many countries to agree to non-proli eration treaties, which attempt to limit nuclear power technologies to a small number o nations.
- A by-product o the peace ul use o uranium or energy production is the creation o plutonium-239 which could be used or the production o nuclear weapons. Is it right or the small number o countries that already have nuclear capability to prevent other countries rom acquiring that knowledge?

FUSION REACTORS

Fusion reactors o er the theoretical potential o significant power generation without many o the problems associated with current nuclear fission reactors. The uel used, hydrogen, is in plenti ul supply and the reaction (i it could be sustained) would not produce significant amounts o radioactive waste.

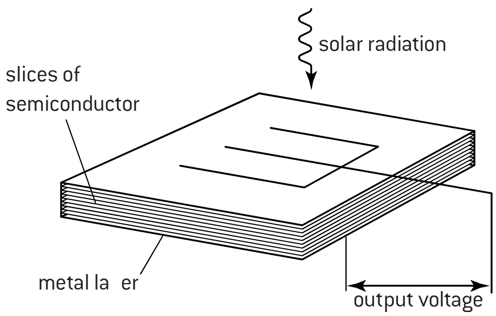
The reaction is the same as takes place in the Sun (as outlined on page 76) and requires creating temperatures high enough to ionize atomic hydrogen into a plasma state (this is the ' ourth state o matter', in which electrons and protons are not bound in atoms but move independently). Currently the principal design challenges are associated with maintaining and confining the plasma at su ficiently high temperature and density or usion to take place.

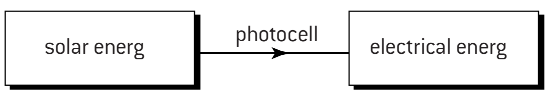
Solar po er and hydroelectric po er

SOLAR POWER (TWO TYPES)

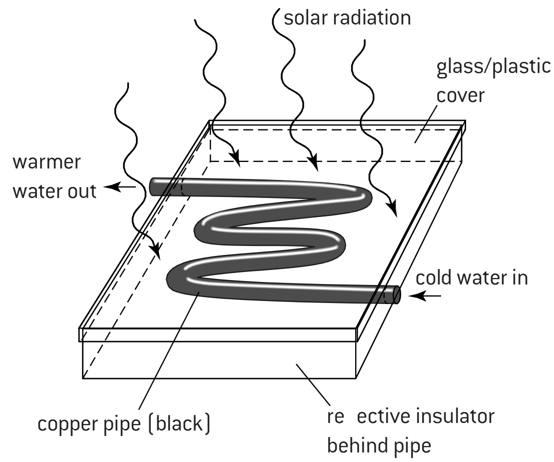
There are two ways of harnessing the radiated energy that arrives at the Earth's surface from the Sun.

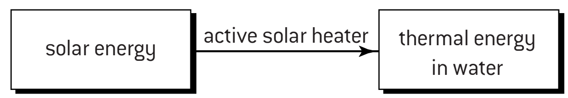
A **photovoltaic cell** (otherwise known as a solar cell or photocell) converts a portion of the radiated energy directly into a potential difference ('voltage'). It uses a piece of semiconductor to do this. Unfortunately, a typical photovoltaic cell produces a very small voltage and it is not able to provide much current. They are used to run electrical devices that do not require a great deal of energy. Using them in series would generate higher voltages and several in parallel can provide a higher current.





An **active solar heater** (otherwise known as a solar panel) is designed to capture as much thermal energy as possible. The hot water that it typically produces can be used domestically and would save on the use of electrical energy.





ADVANTAGES AND DISADVANTAGES

Ad antages

- Very 'clean' production – no harmful chemical by-products.
- Renewable source of energy.
- Source of energy is free.

Disad antages

- Can only be utilized during the day.
- Source of energy is unreliable – could be a cloudy day.
- A very large area would be needed for a significant amount of energy.

HYDROELECTRIC POWER

The source of energy in a hydroelectric power station is the gravitational potential energy of water. If water is allowed to move downhill, the flowing water can be used to generate electrical energy.

The water can gain its gravitational potential energy in several ways.

- As part of the 'water cycle', water can fall as rain. It can be stored in large reservoirs as high up as is feasible.
- Tidal power schemes trap water at high tides and release it during a low tide.
- Water can be pumped from a low reservoir to a high reservoir. Although the energy used to do this pumping must be more than the energy regained when the water flows back down hill, this '**pumped storage**' system provides one of the few large-scale methods of storing energy.

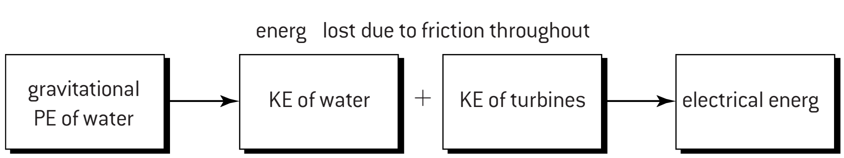
ADVANTAGES AND DISADVANTAGES

Ad antages

- Very 'clean' production – no harmful chemical by-products.
- Renewable source of energy.
- Source of energy is free.

Disad antages

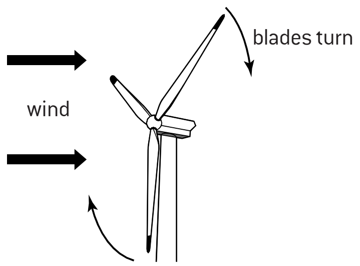
- Can only be utilized in particular areas.
- Construction of dams will involve land being submerged under water.

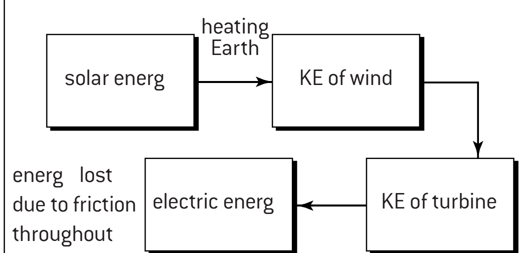


Wind po er and other technologies

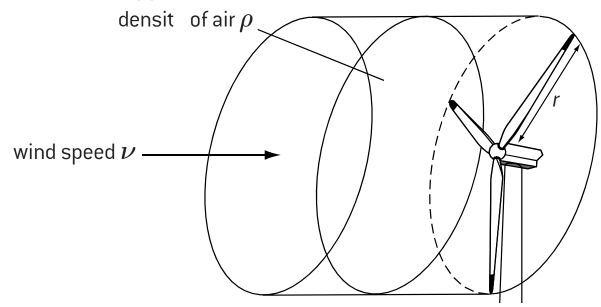
ENERGY TRANSFORMATIONS

There is a great deal o kinetic energy involved in the winds that blow around the Earth. The original source o this energy is, o course, the Sun. Di erent parts o the atmosphere are heated to di erent temperatures. The temperature di erences cause pressure di erences, due to hot air rising or cold air sinking, and thus air flows as a result.





MATHEMATICS



The area 'swept out' by the blades o the turbine = $A = \pi r^2$

In one second the volume o air that passes the turbine = A

So mass o air that passes the turbine in one second = $A\rho$

Kinetic energy m available per second = $\frac{1}{2} m\ ^2$

$= \frac{1}{2}(\ A\rho)\ ^2$

$= \frac{1}{2} A\rho\ ^3$

In other words, power available = $\frac{1}{2} A\rho\ ^3$

In practice, the kinetic energy o the incoming wind is easy to calculate, but it cannot all be harnessed as the air must continue to move – in other words the wind turbine cannot be one hundred per cent e ficient. A doubling o the wind speed would mean that the available power would increase by a actor o eight.

ADVANTAGES AND DISADVANTAGES

Ad antages

- Very 'clean' production – no harm ul chemical by-products.
- Renewable source o energy.
- Source o energy is ree.

Disad antages

- Source o energy is unreliable – could be a day without wind.
- A very large area would need be covered or a significant amount o energy.
- Some consider large wind generators to spoil the countryside.
- Can be noisy.
- Best positions or wind generators are o ten ar rom centres o population.

SECONDARY ENERGY SOURCES

By ar the most common primary energy sources in use worldwide are the three main ossil uels: oil, coal and natural gas. With the inclusion o uranium, at the time o writing this guide, this accounts or 90% o the world's energy consumption. Other primary uels include the renewables: solar, wind, tidal, biomass and geothermal.

With global energy demand expected to rise in the uture, the hope is that developments with renewable energy can help to reduce the dependence on ossil uels.

Primary energy sources are not convenient or individual users and typically a conversion process takes place that results in a **secondary energy source** that can be widely used in society. The most common secondary sources are electrical energy (a very versatile secondary source) or refined uels (e.g. petrol).

The storage o electrical energy is a challenge, with everyday devices (e.g. batteries or capacitors) having a very limited capability when compared with typical everyday demands. Power companies need to vary the generation o electrical energy to match consumer demand. Currently pumped storage hydroelectric systems are the only viable large-scale method o storing spare electrical energy capacity or uture use. The e ficiency o a typical system is approximately 75% meaning that one quarter o the energy supplied is wasted.

NEW AND DEVELOPING TECHNOLOGIES

It is impossible to predict technological developments that are going to take place over the coming years. Current models, however, predict a continuing dependence on the use o ossil uels or many years to come. The hope is that we will be able to decrease this dependency over time. It is important to be aware o the development o new technologies particularly those associated with:

- renewable energy sources
- improving the e ficiency o our energy conversion process.

Thermal energy transfer

PROCESSES OF THERMAL ENERGY TRANSFER

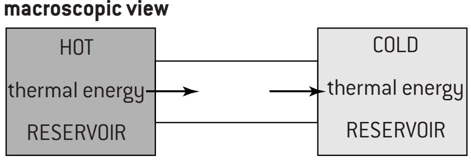
There are several processes by which the transfer of thermal energy from a hot object to a cold object can be achieved. Three very important processes are called **conduction**, **convection** and **radiation**. Any given practical situation probably involves more than one of these processes happening at the same time. There is a fourth process called **evaporation**. This involves the faster moving molecules leaving the surface of a liquid that is below its boiling point. Evaporation causes cooling.

CONDUCTION

In thermal conduction, thermal energy is transferred along a substance without any bulk (overall) movement of the substance. For example, one end of a metal spoon soon feels hot if the other end is placed in a hot cup of tea.

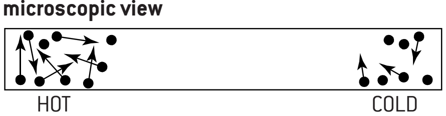
Conduction is the process by which kinetic energy is passed from molecule to molecule.

macroscopic view



Thermal energy ows along the material as a result of the temperature difference across its ends.

microscopic view



The faster-moving molecules at the hot end pass on their kinetic energy to the slower-moving molecules as a result of intermolecular collisions.

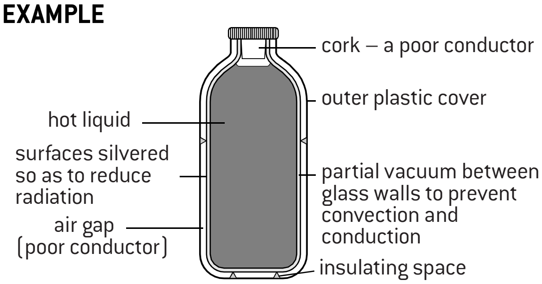
Points to note:

- Poor conductors are called thermal **insulators**.
- Metals tend to be very good thermal conductors. This is because a different mechanism (involving the electrons) allows quick transfer of thermal energy.
- All gases (and most liquids) tend to be poor conductors.

Examples:

- Most clothes keep us warm by trapping layers of air – a poor conductor.
- If one walks around a house in bare feet, the floors that are better conductors (e.g. tiles) will feel colder than the floors that are good insulators (e.g. carpets) even if they are at the same temperature. (For the same reason, on a cold day a piece of metal feels colder than a piece of wood.)
- When used for cooking food, saucepans conduct thermal energy from the source of heat to the food.

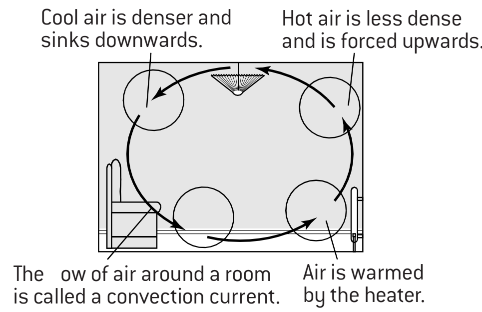
EXAMPLE



A thermos flask prevents heat loss

CONVECTION

In convection, thermal energy moves between two points because of a bulk movement of matter. This can only take place in a **fluid** (a liquid or a gas). When part of the fluid is heated it tends to expand and thus its density is reduced. The colder fluid sinks and the hotter fluid rises up. Central heating causes a room to warm up because a **convection current** is set up as shown below.



Convection in a room

Points to note:

- Convection cannot take place in a solid.

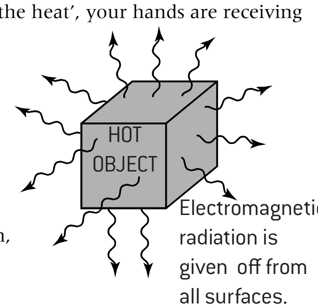
Examples:

- The pilots of gliders (and many birds) use naturally occurring convection currents in order to stay above the ground.
- Sea breezes (winds) are often due to convection. During the day the land is hotter than the sea. This means hot air will rise from above the land and there will be a breeze onto the shore. During the night, the situation is reversed.
- Lighting a fire in a chimney will mean that a breeze flows in the room towards the fire.

RADIATION

Matter is not involved in the transfer of thermal energy by radiation. All objects (that have a temperature above zero kelvin) radiate **electromagnetic waves**. If you hold your hand up to a fire to 'feel the heat', your hands are receiving the radiation.

For most everyday objects this radiation is in the **in ra-red** part of the **electromagnetic spectrum**. For more details of the electromagnetic spectrum, see page 37.



Points to note:

- An object at room temperature absorbs and radiates energy. If it is at constant temperature (and not changing state) then the rates are the same.
- A surface that is a good radiator is also a good absorber.
- Surfaces that are light in colour and smooth (shiny) are poor radiators (and poor absorbers).
- Surfaces that are dark and rough are good radiators (and good absorbers).
- If the temperature of an object is increased then the frequency of the radiation increases. The total rate at which energy is radiated will also increase.
- Radiation can travel through a vacuum (space).

Examples:

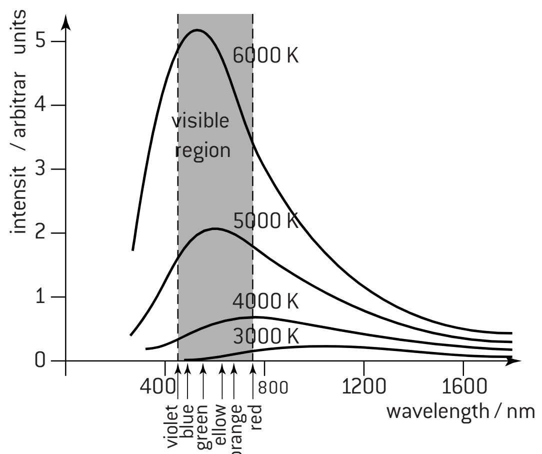
- The Sun warms the Earth's surface by radiation.
- Clothes in summer tend to be white – so as not to absorb the radiation from the Sun.

Radiation: Wien's law and the Stefan–Boltzmann law

BLACK-BODY RADIATION: STEFAN-BOLTZMANN LAW

In general, the radiation given out rom a hot object depends on many things. It is possible to come up with a theoretical model or the 'per ect' emitter o radiation. The 'per ect' emitter will also be a per ect absorber o radiation – a black object absorbs all o the light energy alling on it. For this reason the radiation rom a theoretical 'per ect' emitter is known as **black-body radiation**.

Black-body radiation does not depend on the nature o the emitting sur ace, but it does depend upon its temperature. At any given temperature there will be a range o di erent wavelengths (and hence requencies) o radiation that are emitted. Some wavelengths will be more intense than others. This variation is shown in the graph below.



To be absolutely precise, it is not correct to label the y-axis on the above graph as the intensity, but this is o ten done. It is actually something that could be called the intensity unction. This is defined so that the area under the graph (between two wavelengths) gives the intensity emitted in that wavelength range. The total area under the graph is thus a measure o the total power radiated. The power radiated by a Black-body (See page 195) is given by:

Surface area in m² — absolute temperature in kelvins

$$P = \ \ AT^4$$

Total power radiated in W — *Stefan-Boltzmann constant*

Although stars and planets are not per ect emitters, their radiation spectrum is approximately the same as black-body radiation.

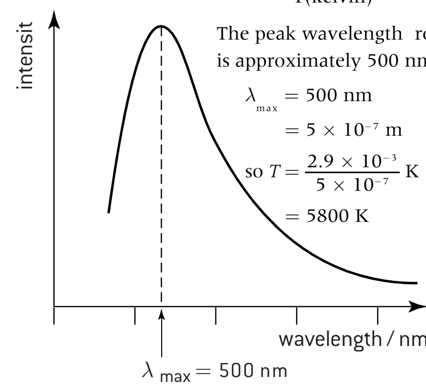
WIEN'S LAW

Wien's displacement law relates the wavelength at which the intensity o the radiation is a maximum λ_{max} to the temperature o the black body T. This states that

$$\lambda_{max}\, T = \text{constant}$$

The value o the constant can be ound by experiment. It is 2.9×10^{-3} m K. It should be noted that in order to use this constant, the wavelength should be substituted into the equation in metres and the temperature in kelvin.

$$\lambda_{max}\ (\text{metres}) = \frac{2.90 \times 10^{-3}}{T(\text{kelvin})}$$



The peak wavelength rom the Sun is approximately 500 nm.

$$\lambda_{max} = 500 \text{ nm}$$
$$= 5 \times 10^{-7} \text{ m}$$
$$\text{so } T = \frac{2.9 \times 10^{-3}}{5 \times 10^{-7}} \text{ K}$$
$$= 5800 \text{ K}$$

We can analyse light rom a star and calculate a value or its sur ace temperature. This will be much less than the temperature in the core. Hot stars will give out all requencies o visible light and so will tend to appear white in colour. Cooler stars might well only give out the higher wavelengths (lower requencies) o visible light – they will appear red. Radiation emitted rom planets will peak in the in ra-red.

INTENSITY, I

The intensity o radiation is the power per unit area that is received by the object. The unit is W m^{-2}.

$$I = \frac{\text{Power}}{A}.$$

EQUILIBRIUM AND EMISSIVITY

I the temperature o a planet is constant, then the power being absorbed by the planet must equal the rate at which energy is being radiated into space. The planet is in **thermal equilibrium**. I it absorbs more energy than it radiates, then the temperature must go up and i the rate o loss o energy is greater than its rate o absorption then its temperature must go down.

In order to estimate the power absorbed or emitted, the ollowing concepts are use ul.

Emissivit

The Earth and its atmosphere are not a per ect black body. Emissivity, *e*, is defined as the ratio o power radiated per unit area by an object to the power radiated per unit area by a black body at the same temperature. It is a ratio and so has no units.

$$e = \frac{\text{power radiated by object per unit area}}{\text{power radiated per unit area by black body at same temperature}}$$

thus

$$p = e\sigma A T^4$$

ALBEDO

Some o the radiation received by a planet is reflected straight back into space. The raction that is reflected back is called the **albedo**, α.

The Earth's albedo varies daily and is dependent on season (cloud ormations) and latitude. Oceans have a low value but snow has a high value. The global annual mean albedo is 0.3 (30%) on Earth.

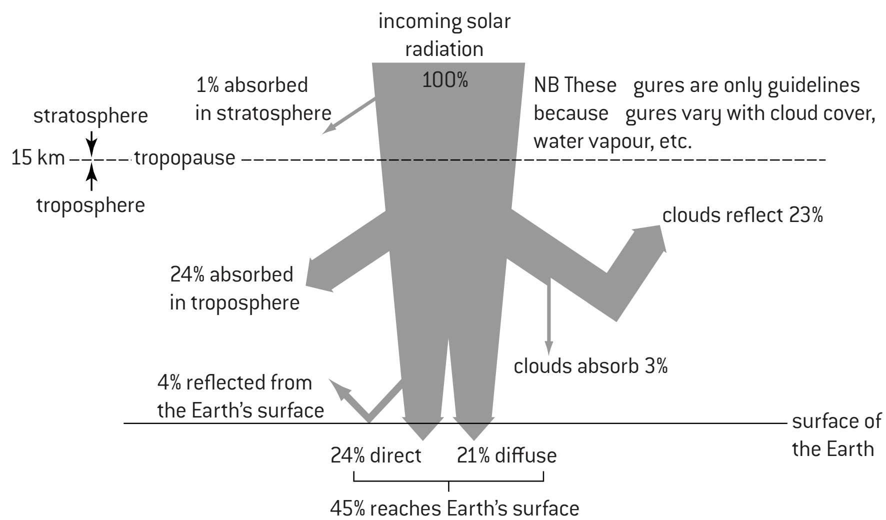
$$\text{albedo} = \frac{\text{total scattered power}}{\text{total incident power}}$$

So ar power

SOLAR CONSTANT

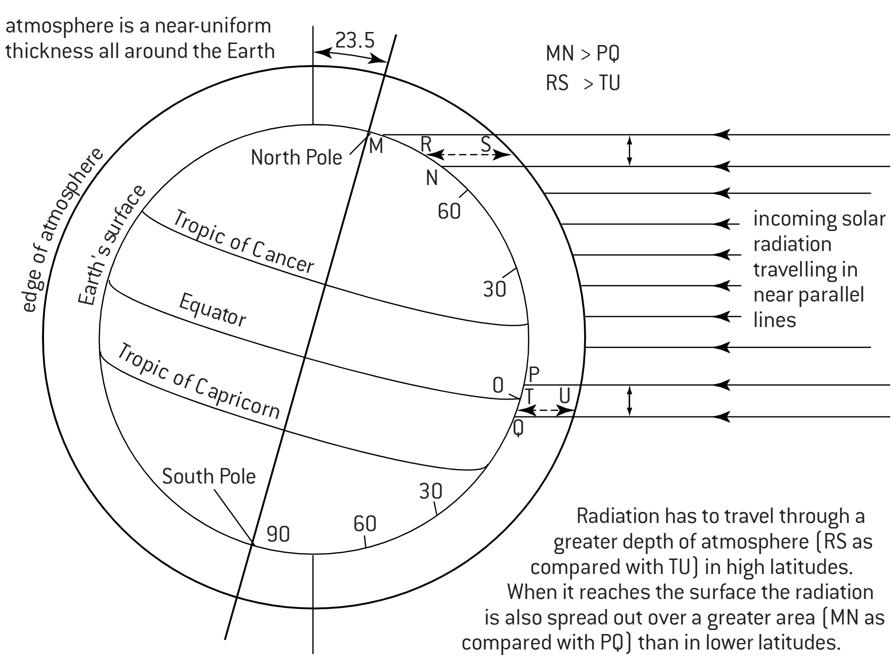
The amount of power that arrives from the Sun is measured by the solar constant. It is properly defined as the amount of solar energy that falls per second on an area of 1 m^2 above the Earth's atmosphere that is at right angles to the Sun's rays. Its average value is about 1400 $W\,m^{-2}$.

This is not the same as the power that arrives on 1 m^2 of the Earth's surface. Scattering and absorption in the atmosphere means that often less than half of this arrives at the Earth's surface. The amount that arrives depends greatly on the weather conditions.

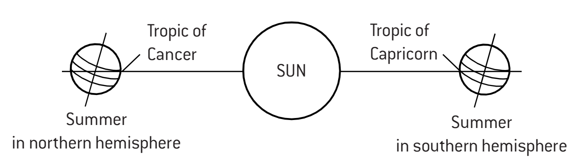


Fate of incoming radiation

Different parts of the Earth's surface (regions at different latitudes) will receive different amounts of solar radiation. The amount received will also vary with the seasons since this will affect how spread out the rays have become.



The effect of latitude on incoming solar radiation



The Earth's orbit and the seasons

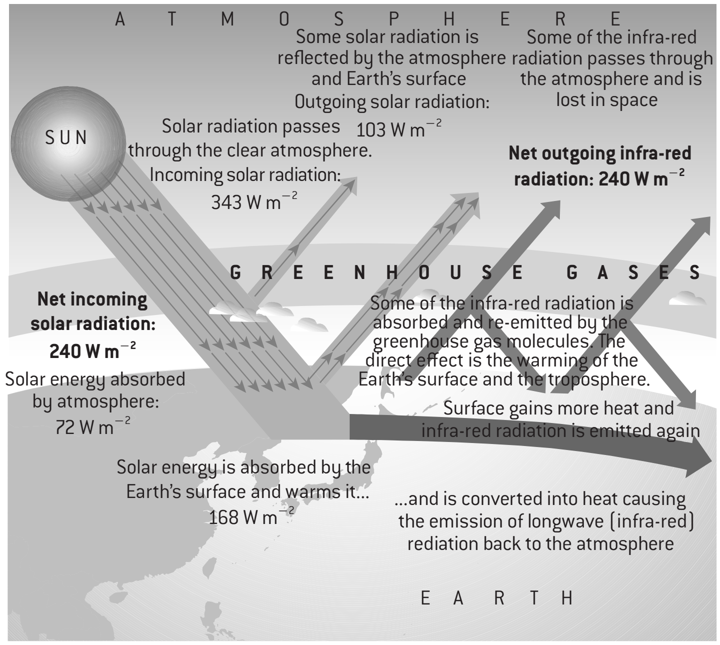
The greenhouse effect

PHYSICAL PROCESSES

Short wavelength radiation is received from the Sun and causes the surface of the Earth to warm up. The Earth will emit infra-red radiation (longer wavelengths than the radiation coming from the Sun) because the Earth is cooler than the Sun. Some of this infra-red radiation is absorbed by gases in the atmosphere and re-radiated in all directions.

This is known as the **greenhouse e ect** and the gases in the atmosphere that absorb infra-red radiation are called **greenhouse gases**. The net effect is that the upper atmosphere and the surface of the Earth are warmed. The name is potentially confusing, as real greenhouses are warm as a result of a different mechanism.

The temperature of the Earth's surface will be constant if the rate at which it radiates energy equals the rate at which it absorbs energy. The greenhouse effect is a natural process and without it the temperature of the Earth would be much lower; the average temperature of the Moon is more than 30 °C colder than the Earth.



Sources: Okanagan University College in Canada; Department of Geography, University of Oxford; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the Intergovernmental Panel on Climate Change, UNEP and WMO, Cambridge Press, 1996

GREENHOUSE GASES

The main greenhouse gases are naturally occurring but the balance in the atmosphere can be altered as a result of their release due to industry and technology. They are:

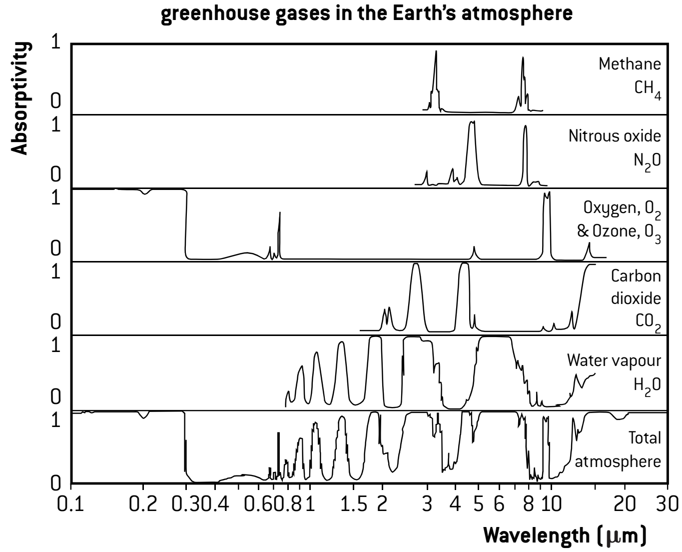
- **Methane**, CH_4. This is the principal component of natural gas and the product of decay, decomposition or fermentation. Livestock and plants produce significant amounts of methane.
- **Water**, H_2O. The small amounts of water vapour in the upper atmosphere (as opposed to clouds which are condensed water vapour) have a significant effect. The average water vapour levels in the atmosphere do not appear to alter greatly as a result of industry, but local levels can vary.
- **Carbon dioxide**, CO_2. Combustion releases carbon dioxide into the atmosphere which can significantly increase the greenhouse effect. Overall, plants (providing they are growing) remove carbon dioxide from the atmosphere during photosynthesis. This is known as **carbon fixation**.
- **Nitrous oxide**, N_2O. Livestock and industries (e.g. the production of Nylon) are major sources of nitrous oxide. Its effect is significant as it can remain in the upper atmosphere for long periods.

In addition the following gases also contribute to the greenhouse effect:

- **Ozone**, O_3. The **ozone layer** is an important region of the atmosphere that absorbs high energy UV photons which would otherwise be harmful to living organisms. Ozone also adds to the greenhouse effect.
- **Chlorofluorocarbons** (CFCs). Used as refrigerants, propellants and cleaning solvents. They also have the effect of depleting the ozone layer.

Each of these gases absorbs infra-red radiation as a result of resonance (see page 168). The natural frequency of oscillation of the bonds within the molecules of the gas is in the infra-red region. If the driving frequency (from the radiation emitted from the Earth) is equal to the natural frequency of the molecule, resonance will occur. The amplitude of the molecules' vibrations increases and the temperature will increase. The absorption will take place at specific frequencies depending on the molecular energy levels.

Absorption spectra for major natural greenhouse gases in the Earth's atmosphere

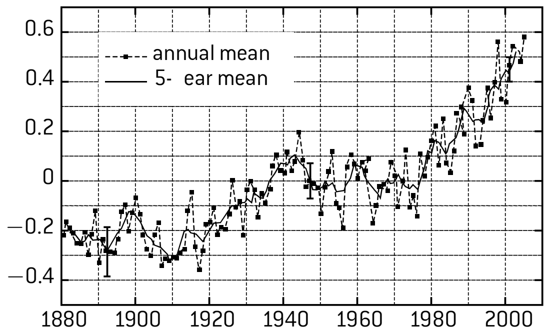


[After J.N. Howard, 1959: *Proc. I.R.E. 47*, 1459: and R.M. Goody and G.D. Robinson, 1951: *Quart. J. Roy Meteorol. Soc. 77*, 153]

Global arming

POSSIBLE CAUSES OF GLOBAL WARMING

Records show that the mean temperature of the Earth has been increasing in recent years.



All atmospheric models are highly complicated. Some possible suggestions for this increase include.

- Changes in the composition of greenhouse gases in the atmosphere.
- Changes in the intensity of the radiation emitted by the Sun linked to, for example, increased solar flare activity.
- Cyclical changes in the Earth's orbit and volcanic activity.

The first suggestion could be caused by natural effects or could be caused by human activities (e.g. the increased burning of fossil fuels). An **enhanced greenhouse effect** is an increase in the greenhouse effect caused by human activities.

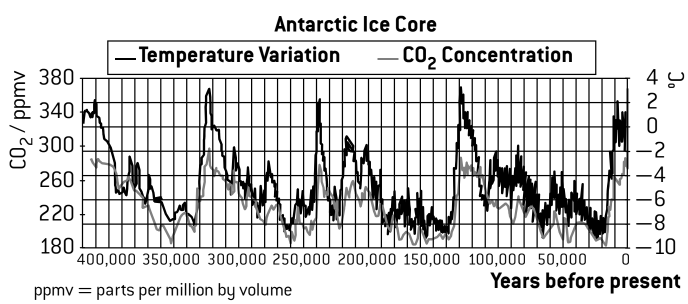
In 2013, the IPCC (Intergovernmental Panel on Climate Change) report stated that 'It is extremely likely that human influence has been the dominant cause of the observed warming since the mid–20th century'.

Although it is still being debated, the generally accepted view is that that the increased combustion of fossil fuels has released extra carbon dioxide into the atmosphere, which has enhanced the greenhouse effect.

EVIDENCE FOR GLOBAL WARMING

One piece of evidence that links global warming to increased levels of greenhouse gases comes from ice core data. The ice core has been drilled in the Russian Antarctic base at Vostok. Each year's new snow fall adds another layer to the ice.

Isotopic analysis allows the temperature to be estimated and air bubbles trapped in the ice cores can be used to measure the atmospheric concentrations of greenhouse gases. The record provides data from over 400,000 years ago to the present. The variations of temperature and carbon dioxide are very closely correlated.



MECHANISMS

Predicting the future effects of global warming involves a great deal of uncertainty, as the interactions between different systems in the Earth and its atmosphere are extremely complex.

There are many mechanisms that may increase the rate of global warming.

- Global warming reduces ice/snow cover, which in turn reduces the albedo. This will result in an increase in the overall rate of heat absorption.
- Temperature increase reduces the solubility of CO_2 in the sea and thus increases atmospheric concentrations.
- Continued global warming will increase both evaporation and the atmosphere's ability to hold water vapour. Water vapour is a greenhouse gas.
- Regions with frozen subsoil exist (called tundra) that support simple vegetation. An increase in temperature may cause a significant release of trapped CO_2.
- Not only does deforestation result in the release of further CO_2 into the atmosphere, the reduction in number of trees reduces carbon fixation.

The first four mechanisms are examples of processes whereby a small initial temperature increase has gone on to cause a further increase in temperature. This process is known as **positive feedback**. Some people have suggested that the current temperature increases may be 'corrected' by a process which involves negative feedback, and temperatures may fall in the future.

IB Questions – energy production

1. A wind generator converts wind energy into electric energy. The source o this wind energy can be traced back to solar energy arriving at the Earth's sur ace.

   a) Outline the energy trans ormations involved as solar energy converts into wind energy. [2]

   b) List **one** advantage and **one** disadvantage o the use o wind generators. [2]

   The expression or the maximum theoretical power, P, available rom a wind generator is

   $$P = \frac{1}{2}A\rho v^3$$

   where A is the area swept out by the blades,

   ρ is the density o air and

   v is the wind speed.

   c) Calculate the maximum theoretical power, P, or a wind generator whose blades are 30 m long when a 20 m s^{-1} wind blows. The density o air is 1.3 kg m^{-3}. [2]

   d) In practice, under these conditions, the generator only provides 3 MW o electrical power.

   (i) Calculate the e ficiency o this generator. [2]

   (ii) Give **t o** reasons explaining why the actual power output is less than the maximum theoretical power output. [2]

2. This question is about energy sources.

   a) Give **one** example o a renewable energy source and **one** example o a non-renewable energy source and explain why they are classified as such. [4]

   b) A wind arm produces 35,000 MWh o energy in a year. I there are ten wind turbines on the arm show that the average power output o **one** turbine is about 400 kW. [3]

   c) State **t o** disadvantages o using wind power to generate electrical power. [2]

3. This question is about energy trans ormations.

   Wind power can be used to generate electrical energy.

   Construct an energy flow diagram which shows the energy trans ormations, starting with solar energy and ending with electrical energy, generated by windmills. Your diagram should indicate where energy is degraded. [7]

4. This question is about a coal-fired power station which is water cooled.

   Data:

Electrical power output rom the station	= 200 MW
Temperature at which water enters cooling tower	= 288 K
Temperature at which water leaves cooling tower	= 348 K
Rate o water flow through tower	= 4000 kg s^{-1}
Energy content o coal	= 2.8×10^{7} J kg^{-1}
Specific heat o water	= 4200 J kg^{-1} K^{-1}

   Calculate

   a) the energy per second carried away by the water in the cooling tower; [2]

   b) the energy per second produced by burning the coal; [2]

   c) the overall e ficiency o the power station; [2]

   d) the mass o coal burnt each second. [1]

5. This question is about tidal power systems.

   a) Describe the principle o operation o such a system. [2]

   b) Outline **one** advantage and **one** disadvantage o using such a system. [2]

   c) A small tidal power system is proposed. Use the data in the table below to calculate the total energy available and hence estimate the use ul output power o this system.

Height between high tide and low tide	4 m
Trapped water would cover an area o	1.0×10^{6} m^{2}
Density o water	1.0×10^{3} kg m^{-3}
Number o tides per day	2

   [4]

6. Solar power and climate models.

   a) Distinguish, in terms o the energy changes involved, between a solar heating panel and a photovoltaic cell. [2]

   b) State an appropriate domestic use or a

   (i) solar heating panel. [1]

   (ii) photovoltaic cell. [1]

   c) The radiant power o the Sun is 3.90×10^{26} W. The average radius o the Earth's orbit about the Sun is 1.50×10^{11} m. The albedo o the atmosphere is 0.300 and it may be assumed that no energy is absorbed by the atmosphere.

   Show that the intensity incident on a solar heating panel at the Earth's sur ace when the Sun is directly overhead is 966 W m^{-2}. [3]

   d) Show, using your answer to (c), that the average intensity incident on the Earth's sur ace is 242 Wm^{-2}. [3]

   e) Assuming that the Earth's sur ace behaves as a black-body and that no energy is absorbed by the atmosphere, use your answer to (d) to show that the average temperature o the Earth's sur ace is predicted to be 256 K. [2]

) Outline, with re erence to the greenhouse e ect, why the average sur ace temperature o the Earth is higher than 256 K. [4]